NITROGEN MANAGEMENT

Midseason Nitrogen Fertility Management for Corn Based on Weather and Yield Prediction

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ABSTRACT

Nitrogen fertilizer applications for irrigated corn (*Zea mays* L.) based on yield goals established before planting may result in under- or overapplication of N because of weather-induced variations in yield potential from year to year. This study was conducted to develop and evaluate a regression model to predict corn grain yield at a midpoint in the growing season based on the current year's cumulative thermal factors and N fertility levels. The relationship among early-season growing conditions, N fertility, and corn grain yield under continuous corn production and sprinkler irrigation was investigated from 1990–1995 in southeastern North Dakota. Fertility levels on small plots ranged from 0 to 224 kg ha^{-1} applied N. There was a wide range of cumulative growing degree days (GDD) and evapotranspiration (ET) during the study period. Least-squares regression was used to develop equations to predict, on 10 July, grain yield based on cumulative ET or GDD from 1 May to 10 July and soil N plus applied N. Yields predicted on 10 July corresponded well to individual observed yields ($r^2 = 0.80$), and predicted optimum yield (Y_{OPT}) was highly correlated to observed Y_{OPT} ($r^2 = 0.885$). The model could provide a season-specific yield potential used to modify N application during the growing season, resulting in fertilizer savings in the extreme years when cool early-season weather limited yield potential or fertilizer increases to take advantage of optimum growing conditions and increase yields. Including meteorological measurements can improve fertilizer management decisions by providing midseason adjustments to fertilizer recommendations.

PROPER N FERTILIZER MANAGEMENT is crucial for both economic and environmental reasons. Inadequate N fertility results in low yields and lower economic returns while overfertilization can adversely affect surface and ground water resources and also reduce net economic returns. In addition, overfertilization may also result in higher emissions of nitrous oxide—an important greenhouse gas (Kauppi and Sedjo, 2001). Current North Dakota recommendations for fertilizing corn are based on the yield goal concept. This is done by applying 21.4 kg N ha^{-1} for each megagram of corn per hectare expected (yield goal), reduced by the amount of soil test nitrate N (Franzen and Cihacek, 1996). Timely soil test data and reasonable yield goals are required to apply the appropriate amount of N fertilizer using this concept. While the yield goal concept is the accepted approach in North Dakota as well as Minnesota and South Dakota, it may not be suitable for other environments where high soil organic matter and high mineralization reduce the need for N fertilizer to obtain Y_{OPT}. Others have stressed the importance of accurately accounting for the amount of soil N, particularly late-spring nitrate N, when making fertilizer recommendations (Binford et al., 1992; Blackmer et al., 1989; Vanotti and Bundy, 1994) and have determined relationships between soil nitrate N and yield. Similarly, Bundy and Malone (1988) found no increase in yield to applied N when soil nitrate levels were high, emphasizing the need for soil test data for accurate fertilizer recommendations.

Previous work indicates that yield goal selection should also be based, to some degree, on soil factors (not simply the maximum desired yield) to produce a more site-specific recommendation (Vanotti and Bundy, 1994; Bundy and Andraski, 1995). Blackmer et al. (1997) recommend, on a site-specific basis, the use of a late-spring soil test to determine the amount of N available before rapid crop N uptake. They also recommended that yield goals no longer be used because much of the N taken up by the crop is supplied by the soil. Additionally, they address weather's role in modifying N recommendation where heavy spring rainfall may leach plant available N from the root zone or warm conditions may increase mineralization and available N.

The relationship of corn maturity to air temperature and cumulative GDD in the Northern Great Plains is well established. Runge (1968) found a high correlation between corn yield and ET (rainfall and maximum daily temperature). Wienhold et al. (1995) noted no difference in yield between two fertility levels when growing season temperatures were below normal and observed the lowest yields in a year with below-average cumulative GDD. Several studies have indicated that a given corn variety requires a minimum number of heat units throughout the growing season to reach maturity (Andrew et al., 1956; Roth and Yocum, 1997; Sutton and Stucker, 1974). This relationship of yield and air temperature (in particular, cumulative GDD) has been used in models to predict corn grain yield (Swan et al., 1990; Bollero et al., 1996; Bauder and Randall, 1982). Taking the prediction one step further, Duchon (1986) used CERES-Maize to predict corn yield at midseason by using historical weather records to fill in the remainder of the year until crop maturity to predict yield. This method assumed N was not limiting.

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Abbreviations: ET, evapotranspiration; ET$_R$, reference evapotranspiration; GDD, growing degree days; SA-N, soil nitrogen plus applied nitrogen; Y_{OPT}, optimum yield.

Knowledge of the effects of N fertility and yearly weather fluctuations in the form of ET or heat unit accumulation needs to be combined to develop better fertilizer management practices. The objective of this study was to develop and evaluate a regression model to predict final corn grain yield at a midpoint in the growing season based on the current year's cumulative thermal factors and N fertility levels. This predicted yield could then be used as a new projected yield goal for that year. Adjustments in the midseason N application recommendations could then be based on this new projected yield goal. The result would be reduced N applications when climatic conditions are less than favorable for maximum yield. Conversely, increased N application may be warranted in years with ideal growing conditions in anticipation of higher yields.

METHODS

Site Description

The site was a 64-ha sprinkler-irrigated field located in southeastern North Dakota (46°2′60″ N, 98°6′36″ W; elevation 397 m). The site was dominated by Hecla loamy fine sand soil (sandy, mixed, frigid Oxyaquic Hapludoll) in the area of the field where the plots described here were located (Fig. 1). Eighteen small plots were located in the southeast quadrant of the field, and 18 were located in the northeast quadrant. Each plot was 9.1 m wide (12 corn rows) and 18.3 m long. Six plots were arranged in two-plot-wide by three-plot long blocks. The plots in the southeast quadrant were used for model development while the northeast plots were used for validation. The organic matter content of the top 30 cm is 1.8%. The site was not irrigated before 1989 and was planted to corn (cv. Pioneer 3737) in 1989–1995. Each year, irrigation was scheduled according to different methods in each quasi-quadrant (see Fig. 1), each based on measured or predicted soil moisture status and crop water use (Steele et al., 2000).

Fertilizer Application

From 1990–1995, the plots received N fertilizer treatments ranging from 0 (Treatment A) to 225 (Treatment F) kg N ha^{-1} in 45 kg N ha^{-1} increments in single or split applications, depending upon the rate. The B and C treatments (45 and 90 kg N ha^{-1}) were applied in mid-June at the six-leaf (V6) stage. All other treatments (D, E, and F) also received 90 kg N ha^{-1} at that time. In mid-July at the 15-leaf stage (V15), an additional 45 kg N ha^{-1} was applied to the D treatments and
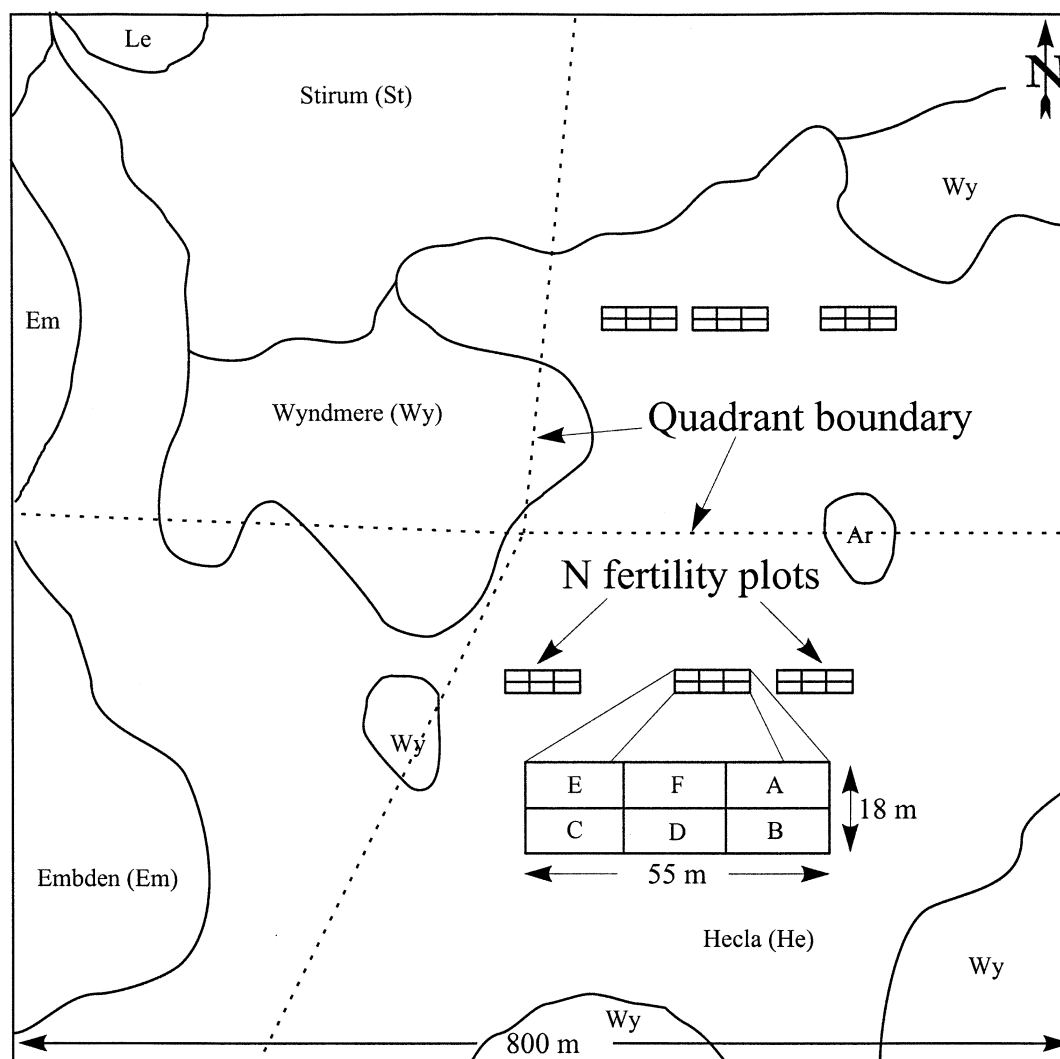

Fig. 1. Map of plot locations and soil types. One block of plots was expanded to show randomized N treatments. A = 0, B = 45, C = 90, D = 135, E = 180, and F = 225 kg ha^{-1} fertilizer N.

90 kg N ha^{-1} to the E and F treatments. In early August at silking (R1), the final application of 45 kg N ha^{-1} was made to the F plots. Applications at V6 were done by injecting urea ammonium nitrate solution adjacent to the rows. Urea was hand-applied in the rows at V15 and R1 and incorporated by irrigation. Starter fertilizer was applied at planting at the rate of 13 kg N ha^{-1} in 1991–1993, 48 kg N ha^{-1} in 1994, and 11 kg N ha^{-1} in 1995. This amount was considered in the total N applied.

Soil and Plant Sampling

Soil nitrate N was measured in the center of each plot to a depth of 61 cm each year in early June. Two between-row soil cores from each plot were composited and subsampled. Samples were placed in plastic zip-top bags and frozen until 2 M KCl extracts and nitrate N analysis (EPA Method 353.2, USEPA, 1983) could be done. The sum of soil test nitrate N and applied fertilizer N will now be referred to as soil N plus applied N (SA-N).

Representative areas 4.6 m long and two rows wide were hand-harvested in the center four rows of each plot for final grain yield after maturity (R6). Ears were separated from the plants, dried, shelled, and weighed for yield determination (corrected to 15.5% moisture on a dry weight basis). Optimum grain yields (Y_{OPT}) were calculated from the yield vs. SA-N relationship for each year by differentiating the quadratic function of the relationship. A quadratic model for yield vs. SA-N was used since it is the most widely used for describing plant nutrient responses (Blackmer et al., 1989).

Growing Degree Days and Evapotranspiration Calculations

Maximum and minimum air temperature, precipitation, and solar radiation were measured at an automated weather station located 2.7 km from the site. Irrigation and precipitation were also measured on-site. The normal (1960–1990) maximum and minimum temperatures for 1 May through 30 September were 25.2 and 10.4°C, respectively, and normal 1 May through 30 September rainfall was 316 mm.

The method for GDD calculation was the mean daily air temperature minus 10°C, with bases of 10 and 30°C for the minimum and maximum temperatures, respectively (Cross and Zuber, 1972; Gilmore and Rogers, 1958). Daily ET was calculated by five methods: (i) reference ET (denoted here as ET_R) by the method of Jensen and Haise (1963), which uses mean daily air temperature and daily solar radiation to calculate ET_R; (ii) estimates of corn ET by the water balance or *checkbook* (CBK ET) approach of Lundstrom and Stegman (1988), which calculates average corn water use based on daily maximum air temperature and weeks after emergence; (iii) the ET algorithm of Stegman and Coe (1984), which is a modification of the Jensen–Haise ET_R using a fourth-order polynomial ET crop curve based on days past emergence, percentage available soil water, and adjustments for a wet soil surface after rain or irrigation (denoted as Stegman DPE ET); (iv) an ET crop curve developed by Sajid (see Steele et al., 1996) that is another modification of the Jensen–Haise ET_R that uses a fifth-order polynomial crop curve with a days-past-planting base developed from 11 yr of nonweighing lysimeter data (denoted as Sajid DPP ET); and (v) Sajid GDD ET, which is the same as the Sajid DPP ET except that GDD since planting is used as the time base for the ET crop curve. The ET calculations, with the exception of Jensen–Haise, were specific to southeastern ND.

Growing degree day and ET values accumulated beginning at either 1 May, planting, or emergence until 10 July and until crop maturity or 30 Sept, depending on the method, are listed in Table 1. The cutoff date chosen for midseason GDD and ET accumulation was 10 July because it was the approximate date of the second (V15) fertilizer split application and the latest time in the season to reasonably apply additional N. This is also during a period of very rapid N uptake (Ritchie et al., 1986). A revised yield estimate must be available at this time to make an adjustment, if needed, in the remaining balance of N fertilizer to be applied.

Statistics

Statistical analysis was performed using the SAS JMP software (SAS Inst., 1994) Fit Model and Fit Y by X procedures. Visual inspection of plots of residuals (the difference between observed values and predicted values from the linear regression of yield vs. SA-N) was done to determine if relationships between yield and other variables were linear or quadratic. If the residuals for a linear fit of the data are plotted and the points fall evenly and randomly around the line of zero difference, then the linear method of fitting is valid. If the

Table 1. Cumulative growing degree days (GDD) and evapotranspiration (ET) values through 10 July and end of season for different methods of calculation, observed optimum yield (Y_{OPT}), and water application amounts for each year.

Method	Period	1990	1991	1992	1993	1994	1995
GDD, °C	1 May–10 July	555.8	631.9	536.9	475.6	616.7	543.9
GDD, °C	planting–10 July	528.6	583.1	548.6	458.1	637.8	533.3
ET_R, mm†	1 May–10 July	333.0	339.9	319.8	286.5	355.6	332.0
ET_R, mm	planting–10 July	312.2	307.8	325.9	272.5	363.2	323.9
Stegman DPE ET, mm	emergence–10 July	194.8	219.5	213.6	165.4	203.7	191.8
CBK ET, mm	planting–10 July	132.3	133.4	167.4	132.3	158.8	129.8
Sajid DPP ET, mm	planting–10 July	146.6	113.5	148.6	120.4	204.2	154.2
Sajid GDD ET, mm	planting–10 July	150.4	177.8	158.0	105.9	201.9	156.0
GDD, °C	1 May–30 Sept.	1330.0	1413.6	1188.9	1133.6	1341.9	1332.2
GDD, °C	planting–R6	1271.9	1315.6	1155.3	1079.4	1316.1	1271.7
GDD, °C	planting–30 Sept.	1308.3	1364.7	1205.3	1116.1	1363.1	1321.7
ET_R, mm	1 May–30 Sept.	707.6	715.0	628.9	591.3	706.4	707.1
ET_R, mm	planting–30 Sept.	686.6	682.0	634.5	576.8	714.0	699.3
Stegman DPE ET, mm	planting–30 Sept.	537.2	495.3	458.2	416.1	500.1	515.0
CBK ET, mm	planting–30 Sept.	477.0	477.0	424.7	422.4	446.8	470.9
Sajid DPP ET, mm	planting–30 Sept.	446.3	436.6	378.2	365.3	437.4	465.3
Sajid GDD ET, mm	planting–30 Sept.	464.3	463.8	433.6	383.5	486.2	470.9
Observed Y_{OPT}, Mg ha^{-1}		11.35	10.88	8.06	5.80	13.38	12.16
Irrigation, mm	Apr.–Oct.	192	170	74	53	219	125
Precipitation, mm	Apr.–Oct.	298	436	385	309	417	412
Total, mm	Apr.–Oct.	490	606	459	362	636	537

† ET_R, reference evapotranspiration.

residual points form a quadratic-type pattern relative to the zero difference line, then the relationship is quadratic. This inspection indicated that SA-N was related to yield in a quadratic fashion, 10 July accumulations of GDD and ET were linearly related to yield (Y_{OPT}), and the interaction term of ET $\times$ SA-N was linearly related to yield. Hence, the model for prediction of yield included the SA-N term, SA-N squared term, the GDD or ET term, and the ET or GDD $\times$ SA-N interaction term in the general form of Eq. [1]

$$y_{pred} = C_0 + C_1(\text{SA-N}) + C_2(\text{SA-N})^2 +$$
$$C_3(\text{GDD}_{10Jul} \text{ or } \text{ET}_{10Jul}) +$$
$$C_4(\text{SA-N} \times \text{GDD}_{10Jul} \text{ or } \text{ET}_{10Jul}) \qquad [1]$$

where y_{pred} is predicted yield, C_0 is the y-axis intercept, and C_1, C_2, C_3, and C_4 are the regression estimates.

RESULTS AND DISCUSSION
Corn Variety and Irrigation-Scheduling Methods

The corn variety planted each year, Pioneer 3737, is a 98-d relative maturity hybrid that requires 1304°C GDD to reach maturity, which is appropriate for this latitude (Sutton and Stucker, 1974). Therefore, in normal years, the crop not reaching maturity will not limit the yield. In extremely cool years, however, the crop may not mature fully, resulting in reduced yield.

All irrigation-scheduling methods provided adequate but not excess moisture to replenish the soil water deficit as determined by direct measurement or model prediction. Although yield was slightly affected by irrigation scheduling method over the 1990–1995 study period (at the 0.05 level, $F = 4.13$), the effect of year (weather) was found to be much more significant (at the 0.01 level, $F = 425.8$) (Steele et al., 2000). Irrigation and precipitation amounts are listed in Table 1.

Model Development and Evaluation

Fitting the polynomial yield model (Eq. [1]) using individual plot yields and SA-N data for all years ($n = 108$) and 10 July accumulations of GDD or ET calculated by each of the methods showed that using 1 May through 10 Jul ET_R in the model resulted in the highest r^2 (Table 2). This model will be discussed further while the models that used GDD and the other methods of ET calculation will not be discussed due to the lack of significance or relatively data-intensive calculations. However, the model parameter estimates and summary statistics for all ET and GDD models are included in Table 2 for those who may be interested in the data.

Optimum yields determined from least-squares regression of the observed yield vs. SA-N (the maximum

Table 2. Standard regression model estimates and summary statistics for models to predict yield from soil N plus applied N (SA-N) and growing degree days (GDD) or evapotranspiration (ET), via different methods, accumulated to 10 July. The model is of the form: $y_{pred} = C_0 + C_1(\text{SA-N}) + C_2(\text{SA-N})^2 + C_3(\text{GDD}_{10July} \text{ or } \text{ET}_{10July}) + C_4(\text{SA-N} \times \text{GDD}_{10July} \text{ or } \text{ET}_{10July})$. $n = 108$.

Coefficient	Term	Estimate	Std Error	$P > |t|$	r^2
C_0	Intercept	−8.730642	4.529522	0.0567	0.8049
C_1	SA-N	−0.047805	0.024589	0.0546	
C_2	SA-N²	−0.000116	0.00002	<0.0001	
C_3	ET$_R$ (1May–10July)†	0.0377194	0.014122	0.0088	
C_4	ET$_R$ (1May–10July) × SA-N	0.0003135	0.000078	0.0001	
C_0	Intercept	0.364441	2.088307	0.8618	0.6754
C_1	SA-N	0.0228502	0.012478	0.0700	
C_2	SA-N²	−0.000119	0.000026	<0.0001	
C_3	Sajid GDD ET	0.0196417	0.01358	0.1511	
C_4	Sajid GDD ET × SA-N	0.0002136	0.000074	0.0046	
C_0	Intercept	−2.820752	4.063039	0.4891	0.6536
C_1	SA-N	−0.010579	0.02308	0.6477	
C_2	SA-N²	−0.000108	0.000026	<0.0001	
C_3	GDD (1May–10July)	0.0114864	0.007359	0.1216	
C_4	GDD (1May–10July) × SA-N	0.0001145	0.000041	0.0066	
C_0	Intercept	−1.994542	4.175288	0.6339	0.6327
C_1	SA-N	−0.000492	0.02196	0.9822	
C_2	SA-N²	−0.000119	0.000028	<0.0001	
C_3	GDD (plant–10July)	0.0099921	0.007882	0.2077	
C_4	GDD (plant–10July) × SA-N	0.000104	0.000042	0.0150	
C_0	Intercept	−1.281939	5.03692	0.7996	0.6274
C_1	SA-N	−0.01755	0.025974	0.5008	
C_2	SA-N²	−0.000123	0.000029	<0.0001	
C_3	ET$_R$ (plant–10July)	0.0148092	0.016448	0.3700	
C_4	ET$_R$ (plant–10July) × SA-N	0.0002368	0.000087	0.0079	
C_0	Intercept	2.3688361	2.428981	0.3317	0.5288
C_1	SA-N	0.0278046	0.013681	0.0447	
C_2	SA-N²	−0.000118	0.000033	0.0005	
C_3	Sajid DPP ET	0.0075379	0.01774	0.6718	
C_4	Sajid DPP ET × SA-N	0.0001918	0.000091	0.0384	
C_0	Intercept	1.3994284	5.407268	0.7963	0.4267
C_1	SA-N	0.0036678	0.032206	0.9095	
C_2	SA-N²	−0.000094	0.000033	0.0053	
C_3	Stegman DPE ET	0.0115285	0.027267	0.6733	
C_4	Stegman DPE ET × SA-N	0.0002371	0.000159	0.1381	
C_0	Intercept	12.463699	5.09627	0.0162	0.3439
C_1	SA-N	0.0101358	0.027653	0.7147	
C_2	SA-N²	−0.000099	0.000037	0.0090	
C_3	CBK ET	−0.063401	0.036944	0.0891	
C_4	CBK ET × SA-N	0.0003002	0.000202	0.1398	

† ET$_R$, reference evapotranspiration.

Table 3. Comparison of optimum yields (Y_{OPT}) from observed N response curve and predicted Y_{OPT} from reference evapotranspiration (ET_R) model. Number of observation each year was 18.

| Year	Observed data			Predicted data		Predicted vs. observed Y_{OPT} (1990–1995)	
	Y_{OPT}	95% CI†	Optimum SA-N‡	Y_{OPT}	Optimum SA-N	r^2	p
	——— Mg ha^{-1} ———		kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}		
1990	11.35	9.05–13.65	405.1	10.73	243.9	0.885	0.0051
1991	10.88	9.74–12.02	211.2	11.52	253.2		
1992	8.06	6.36–9.75	245.8	9.26	226.1		
1993	5.80	4.25–7.35	213.0	5.88	181.1		
1994	13.38	8.38–18.39	272.4	13.42	274.5		
1995	12.16	9.99–14.33	238.3	10.62	242.5		

† 95% confidence interval of data used in soil N plus applied N (SA-N) vs. yield response regression.
‡ SA-N, soil N plus applied N.

value from the quadratic yield vs. SA-N curve) were positively correlated to the maximum yields predicted midseason in each year of the study, with $r^2 = 0.89$ and $p = 0.0051$ (Table 3). Predicted maximum yields (ET_R method) were not significantly different than observed Y_{OPT}'s ($\alpha = 0.01$ level) over all years ($t = 0.085$, $t_{0.01} =$

3.36). Predicted vs. observed optimum SA-N was not significantly correlated ($r^2 = 0.367$, $p = 0.279$).

Midseason yield prediction over the range of SA-N for each year was compared with the observed yields in Fig. 2. Predicted yield using the ET_R 10 July accumulation values showed increased yield with increased SA-N
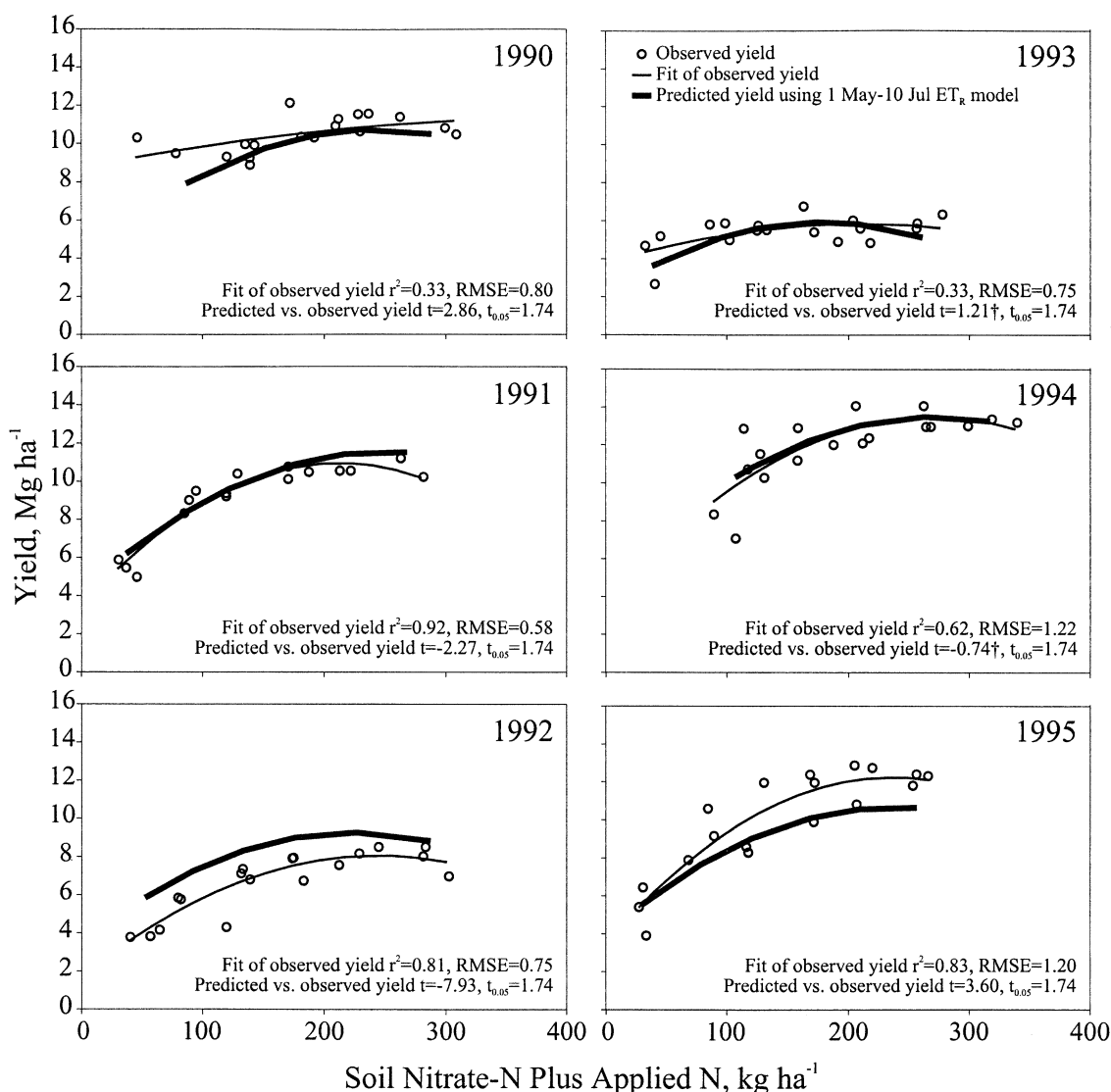
Fig. 2. Yield vs. soil plus applied N (SA-N) regressions for observed yield ($n = 18$) and yield predicted midseason with the reference evapotranspiration (ET_R) model for the range of SA-N values. † Predicted yields not significantly different than observed yields at the 0.05 level.

Table 4. Adjusted yearly yield goals based on midseason prediction using reference evapotranspiration (ET_R) model, associated fertility levels needed to reach yield goals, and potential fertilizer savings. Fertility levels were based on yield goals where 21.4 kg N ha^{-1} was applied for each 1 Mg corn ha^{-1}. The "C" rate plots received no additional fertilizer at V15 of R1 splits.

Year	Observed Y_{OPT}†	Yield goal	Fertility level for yield goal	Adjusted yield goal	Fertility level for adjusted yield goal	Fertilizer savings	Average yield of "C" rate plots
	——— Mg ha^{-1} ———		kg N ha^{-1}	Mg ha^{-1}	——— kg N ha^{-1} ———		Mg ha^{-1}
1990	11.4	12	257	10.7	229	28	10.3 (0.95)‡
1991	10.9	12	257	11.5	247	10	9.6 (0.38)
1992	8.1	12	257	9.2	196	61	7.1 (0.16)
1993	5.8	12	257	5.2	112	145	5.6 (0.09)
1994	13.3	12	257	13.4	286	−29	12.0 (0.49)
1995	12.2	12	257	10.6	227	30	9.6 (1.17)

† Y_{OPT}, optimum yield.
‡ Values in parentheses are standard errors. $n = 3$.

and yearly variations due to early-season temperatures. Paired t-test statistics indicated that the predicted yields were not significantly different than the observed yields for 1993 and 1994 ($t < t_{0.05}$). Although statistically the predicted yields were different than the observed yields for years other than 1993 and 1994, the predicted yields were still visually very close to observed yields for all but 1992 and 1995.

Example of Model Implementation

Since crop growth in 1993 was adversely affected by the cool weather in the spring and the crop did not fully mature before frost on 21 September, we used that year as an example of how the yield prediction model could be used to modify N application midway through the growing season. Based on the farmer's past experience in this portion of the field, the yield goal was set at 12 Mg ha^{-1}. Using the yield goal relationship of 21.4 kg N ha^{-1} for each megagram of corn per hectare resulted in 257 kg N ha^{-1} to be applied under current recommendations (Franzen and Cihacek, 1996). Subtracting the average spring soil test nitrate N from the 18 plots for 1993 (27 kg ha^{-1}) left a balance of 230 kg N ha^{-1} required. The first fertilizer application of 90 kg N ha^{-1} was applied at V6 for a remaining balance of 140 kg N ha^{-1} to be applied. On 10 July 1993, the cumulative ET_R since 1 May was 287 mm. Using ET_R = 287 mm along with 257 kg ha^{-1} for SA-N in the yield prediction equation resulted in a new yield goal of 5.2 Mg ha^{-1}. With the same yield goal relationship of 21.4 kg N ha^{-1} for each megagram of corn per hectare, only 112 kg N ha^{-1} should be applied during the entire growing season to reach maximum yield due to cool early-season growing conditions compared with the original recommendation of 257 kg N

ha^{-1}. This meant a reduction in fertilizer N application of 145 kg N ha^{-1} compared with the original recommendation while still achieving Y_{OPT} for that year. In other words, the original recommendation would have called for 140 kg N ha^{-1} as the required remaining application while use of the yield prediction model indicated that no further applications were needed. This is validated by the fact that the yield from the C treatment plots, i.e., those receiving no further N at the V15 and R1 splits, was basically the same as the 10 July adjusted yield goal and the observed Y_{OPT} (Table 4). Predicted yield (adjusted yield goal) and potential fertilizer savings for all study years are also shown in Table 4. Negative fertilizer savings in 1994 (Table 4) indicated that the yield potential was not met by the level of N fertility and more fertilizer could have been applied to maximize yield.

Model Validation

The model was applied to yield and SA-N data collected from plots in the northeast quadrant of the field for validation. Table 5 shows the observed Y_{OPT}'s and quadratic regression statistics for the northeast plots and how they compared to the predicted Y_{OPT}. The r^2 for predicted vs. observed Y_{OPT}'s was 0.853, and the relationship was significant at the 0.01 level, which indicated that the model was able to predict yield in a different part of the field. Paired t-test analysis also indicated that the predicted and observed Y_{OPT}'s were not significantly different ($t = -2.84$, $t_{0.01} = 3.36$).

The model was also applied to data collected from an independent producer's field (denoted as Test Area) located approximately 3 km from the study site. The

Table 5. Comparison of model-predicted optimum yield (Y_{OPT}) to Y_{OPT} from the quadratic yield vs. soil N plus applied N (SA-N) response curve from the northeast plots. Number of observations for each year is 18.

Year	Predicted Y_{OPT}	Observed Y_{OPT}	r^2	RMSE	p	r^2	p
		Observed yield vs. SA-N relationship for northeast plots				Predicted vs. observed Y_{OPT} (1990–1995)	
	——— Mg ha^{-1} ———						
1990	10.73	10.50	0.775	0.867	<0.0001	0.853	0.0085
1991	11.52	9.23	0.490	1.991	0.0064		
1992	9.26	6.68	0.770	0.826	<0.0001		
1993	5.88	5.49	0.833	0.398	<0.0001		
1994	13.42	12.64	0.941	0.943	<0.0001		
1995	10.62	9.89	0.835	1.542	<0.0001		

Table 6. Measured average yield from an independent producer's field (Test Area) for 1990–1999 compared with model-predicted yield based on applied N and reference evapotranspiration (ET_R) data for those years. Linear regression statistics of observed vs. predicted yield are $r^2 = 0.67$, RMSE = 0.934, and $p = 0.0038$.

Year	Predicted yield	Observed test area yield	Applied N	1 May–10 July ET_R
	——— Mg ha^{-1} ———		kg ha^{-1}	°C
1990	10.40	8.98	191	333
1991	11.23	10.04	203	340
1992	9.20	6.91	248	320
1993	5.84	4.39	200	287
1994	11.04	9.60	131	356
1995	10.62	9.73	244	332
1996	9.06	9.10	202	319
1997	9.28	10.36	187	322
1998	9.76	9.67	230	324
1999	9.91	10.73	231	326

average yield and applied N data from the Test Area field was collected each year and reported in a data set known as the Oakes Irrigation Test Area Agricultural Practices Inventory (API). The API serves as an information base for research and monitoring activities in the Oakes Irrigation Test Area (Esser and Weigel, 1998).

Predicted Y_{OPT}'s for the Test Area field were calculated for years 1990–1999 based on the fertilizer applied and ET_R values for those years. The predicted Y_{OPT} values are compared with the yearly average yields from the Test Area field (Table 6). The linear regression of observed vs. predicted yield for the Test Area field showed a significant correlation at the 0.01 level ($r^2 = 0.67$, $p = 0.0038$), and paired t-test analysis indicated that the predicted and observed yields were not significantly different ($t = -1.96$, $t_{0.01} = 2.82$). These analyses show that the model is capable of predicting yield at different locations and in different years for different varieties.

SUMMARY

Corn grain yield was found to be highly correlated to cumulative ET and was adversely affected by cool spring growing conditions in southeastern North Dakota. A midseason yield prediction model, which used N fertility and a measure of early-season growing conditions (i.e., ET_R), was developed to determine the attainable yield goal before final fertilizer application. It was shown that N application can be adjusted based on an adjusted yield goal, which reduces N applications in extreme years when growing conditions limit yield potential. It can also result in an increase in N application to take advantage of optimum growing conditions and increase yields. Fine-tuning the N application would not necessarily increase yields but would reduce leaching losses of excess nitrate N in extremely cool years and increase profits by reducing input costs. It is important to note that use of this method of fertilizer recommendation adjustment requires a method of fertilizer application that can be done when the crop is 2 m or more tall, such as fertigation through a sprinkler irrigator. Future studies need to be done to further address the implementation of this method.

REFERENCES

Andrew, R.H., F.P. Ferwerda, and A.M. Strommen. 1956. Maturation and yield of corn as influenced by climate and production technique. Agron. J. 48:231–236.

Bauder, J.W., and G.W. Randall. 1982. Regression models for predicting corn yields from climatic data and management practices. Soil Sci. Soc. Am. J. 46:158–161.

Binford, G.D., A.M. Blackmer, and M.E. Cerrato. 1992. Relationship between corn yields and soil nitrate in late spring. Agron. J. 84:53–59.

Blackmer, A.M., D. Pottker, M.E. Cerrato, and J. Web. 1989. Correlations between soil nitrate concentrations in late spring and corn yields in Iowa. J. Prod. Agric. 2:103–109.

Blackmer, A.M., R.D. Voss, and A.P. Mallarino. 1997. Nitrogen fertilizer recommendations for corn in Iowa. Iowa State Univ. Ext. Publ. Pm-1714. Iowa State Univ. Ext., Ames.

Bollero, G.A., D.G. Bullock, and S.E. Hollinger. 1996. Soil temperature and planting date effects on corn yield, leaf area, and plant development. Agron. J. 88:385–390.

Bundy, L.G., and T.W. Andraski. 1995. Soil yield potential effects on performance of soil nitrate tests. J. Prod. Agric. 8:561–568.

Bundy, L.G., and E.S. Malone. 1988. Effect of residual profile nitrate on corn response to applied nitrogen. Soil Sci. Soc. Am. J. 52:1377–1383.

Cross, H.Z., and M.S. Zuber. 1972. Prediction of flowering dates in maize based on different methods of estimating thermal units. Agron. J. 64:351–355.

Duchon, C.E. 1986. Corn yield prediction using climatology. J. Clim. Appl. Meteorol. 25:581–590.

Esser, D.R., and J.K. Weigel. 1998. Agricultural Practices Inventory for the Oakes Test Area study program. p. 351–365. In J. Schaack, A.W. Freitag, and S.S. Anderson (ed.) Proc. 1997 Water Manage. Conf., Fargo, ND. 16–19 July 1997. U.S. Committee on Irrigation and Drainage, Denver.

Franzen, D.W., and L.J. Cihacek. 1996. North Dakota fertilizer recommendation tables and equations based on soil test levels and yield goals. SF-882. North Dakota State Univ. Ext. Serv., Fargo.

Gilmore, E.C., Jr., and J.S. Rogers. 1958. Heat units as a method of measuring maturity in corn. Agron. J. 50:611–615.

Jensen, M.E., and H.R. Haise. 1963. Estimating evapotranspiration from solar radiation. J. Irrig. Drain. Div. Am. Soc. Civ. Eng. 89:15–41.

Kauppi, P., and R. Sedjo. 2001. Technological and economic potential of options to enhance, maintain, and manage biological carbon reservoirs and geo-engineering. p. 301–343. In Metz et al. (ed.) Climate change 2001: Mitigation. Cambridge Univ. Press, Cambridge, UK.

Lundstrom, D.R., and E.C. Stegman. 1988. Irrigation scheduling by the checkbook method. Bull. AE-792 (rev.). North Dakota State Univ. Ext. Serv., Fargo.

Ritchie, S.W., J.J. Hanway, and G.O. Benson. 1986. How a corn plant develops. Spec. Rep. 48 (revised January 1986). Iowa State Univ. of Sci. and Technol. Coop. Ext. Serv., Ames.

Roth, G.W., and J.O. Yocum. 1997. Use of hybrid growing degree day ratings for corn in the northeastern USA. J. Prod. Agric. 10:283–288.

Runge, E.C. 1968. Effects of rainfall and temperature interactions during the growing season on corn yield. Agron. J. 60:503–507.

SAS Institute. 1994. JMP user's guide. Version 3.1.5. SAS Inst., Cary, NC.

Steele, D.D., A.H. Sajid, and L.D. Prunty. 1996. New corn evapotranspiration crop curves for southeastern North Dakota. Trans. ASAE 39(3):931–936.

Steele, D.D., E.C. Stegman, and R.E. Knighton. 2000. Irrigation management for corn in the northern Great Plains, USA. Irrig. Sci. 19:107–114.

Stegman, E.C., and D.A. Coe. 1984. Water balance irrigation scheduling based on Jensen–Haise equation: Software for Apple II, II+ and IIE computers. Res. Rep. 100. North Dakota Agric. Exp. Stn., North Dakota State Univ., Fargo.

Sutton, L.M., and R.E. Stucker. 1974. Growing degree days to black

layer compared to Minnesota relative maturity rating of corn hybrids. Crop Sci. 14:408–412.

Swan, J.B., J.A. Staricka, M.J. Shaffer, W.H. Paulson, and A.E. Peterson. 1990. Corn yield response to water stress, heat units, and management: Model development and calibration. Soil Sci. Soc. Am. J. 54:209–216.

USEPA. 1983. Methods for chemical analysis of water and wastes. EPA-6000/4–79–020 (PB84–128677). U.S. Environ. Monitoring and Support Lab., Cincinnati, OH.

Vanotti, M.B., and L.G. Bundy. 1994. Corn nitrogen recommendations based on yield response data. J. Prod. Agric. 7:249–256.

Wienhold, B.J., T.P. Trooien, and G.A. Reichman. 1995. Yield and nitrogen use efficiency of irrigated corn in the northern Great Plains. Agron. J. 87:842–846.